Simulation of Wave-plasma Interactions and (Extended) MHD in Fusion Systems

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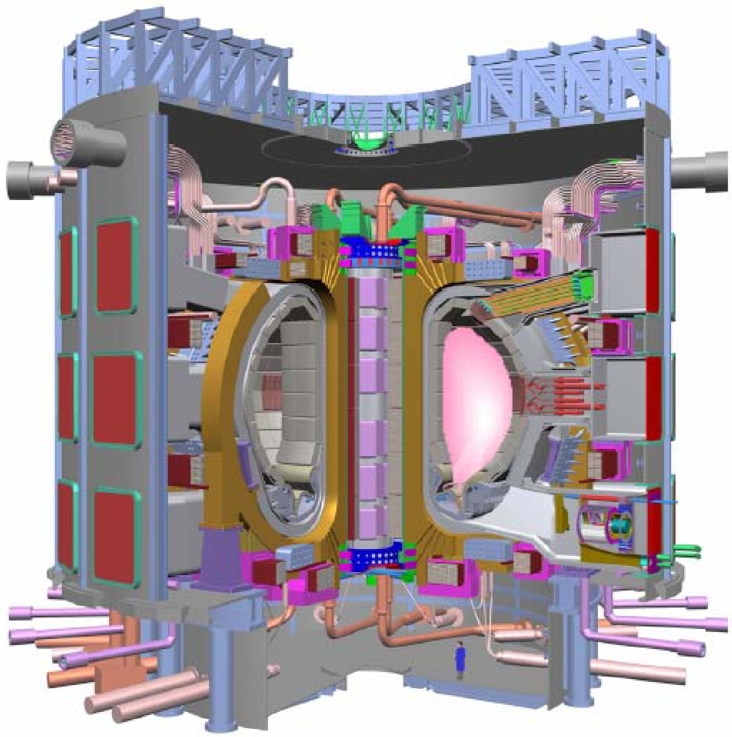
2006 NCCS Users Meeting

- Encompasses three SciDAC projects
  - Center for Simulation of Wave-Plasma Interactions (CSWPI – P. T. Bonoli, PI – MIT)
  - Center for Extended MHD Modeling (CEMM – S. C. Jardin, PI – PPPL)
  - center for Simulation of Wave Interactions with MHD (SWIM – D. B. Batchelor, PI – ORNL)
- Goals of the fusion research program
- High power electromagnetic waves in fusion
- Macroscopic stability of fusion plasmas and extensions into kinetic phenomena
- Bringing the two disciplines together – controlling plasma stability with high power waves

Objective: To develop a secure, reliable energy system using the process that powers the sun, that is environmentally and economically sustainable

Fusion experimental devices throughout the world range in scale from < $50M to ~ $1B

International negotiations are under way to construct a burning test reactor device, ITER, at the ~$5B scale



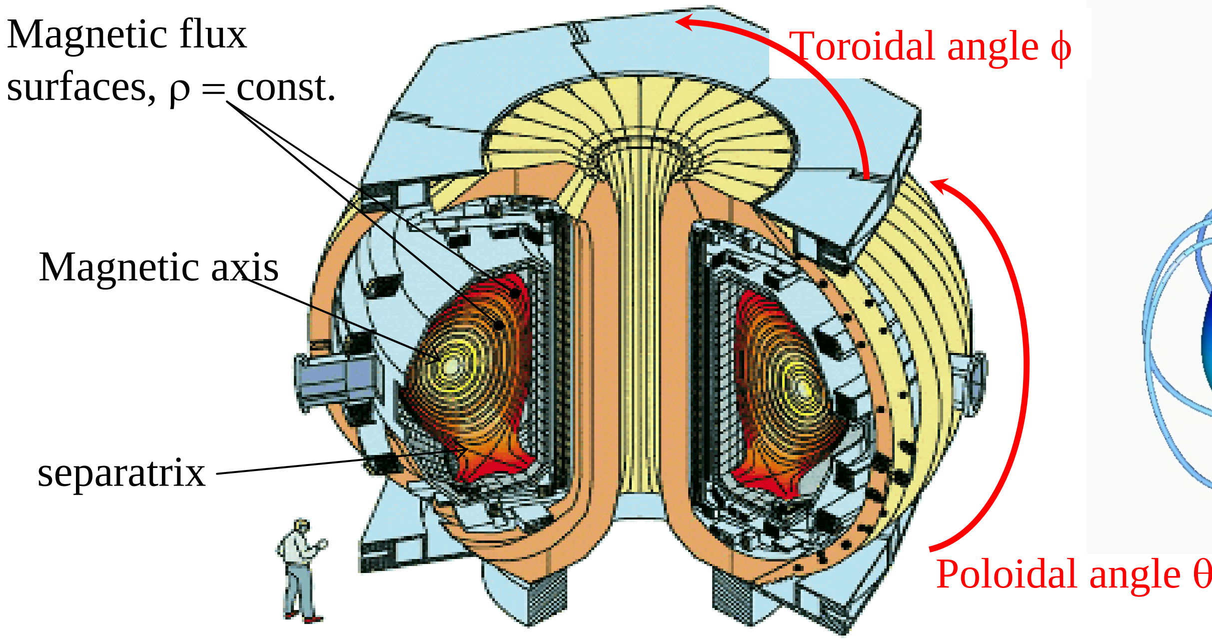
ITER-FEAT

We require massive computations to:

- **Design experiments on fusion devices**
- **Interpret and understand experimental results from devices**
- **Reliably design and evaluate large new machines**
- **Invent and evaluate new, higher performing fusion concepts**

One minute introduction to magnetic fusion

DIII-D Tokamak
axisymmetric



QPS Compact Stellarator
non-axisymmetric!!

- **Sustained fusion reactions require average particle energy ~ 10keV (~100,000,000°K)**

  ⇒ plasma ⇒ magnetic or inertial confinement, no material walls

- **Charged particles move freely along magnetic fields, but can only drift slowly across magnetic fields due to curvature or gradients in field strength.**

- **We can obtain magnetic confinement by using coils and plasma currents to make the field lines wind around the torus both the long way (toroidally) and also the short way (poloidally) to produce closed nested surfaces called flux surfaces.**

Fundamental challenges of fusion simulation

Basic description of plasma is 7D $\rightarrow$ *f*(x, v, t), evolution determined by non-linear Boltzman equation + Maxwell's equations

$$\frac{\partial f}{\partial t} + \mathrm{v}\cdot\nabla f + \tfrac{q}{m}\left[E + \mathrm{v}\times B\right]\cdot\nabla_{\mathrm{v}} f = C(f)$$

convection in space — **convection in velocity space** — **Collisional relaxation toward Maxwellian in velocity space**

$$q(\mathbf{x}) = \int d^3\mathbf{v} f(\mathbf{x},\mathbf{v}) \qquad \mathbf{J}(\mathbf{x}) = \int d^3\mathbf{v}\mathbf{v} f(\mathbf{x},\mathbf{v})$$

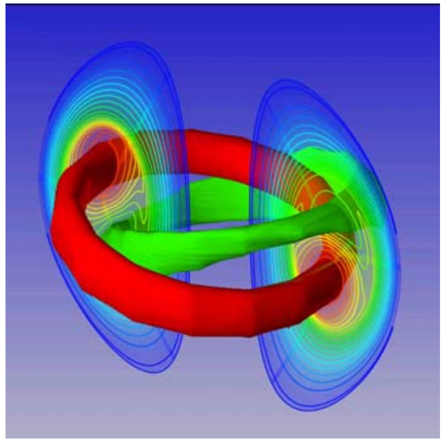
Self -consistent charge and current source densities for Maxwell's eqs obtained from velocity moments

- **High dimensionality**
- **Extreme range of time scales – wall equilibration/electron cyclotron O(10^{14})**
- **Extreme range of spatial scales – machine radius/electron gyroradius O(10^4)**
- **Extreme anisotropy – mean free path in magnetic field parallel/perp O(10^8)**
- **Non-linearity**
- **Sensitivity to geometric details**

To deal with multi-scale, and multi-physics issues several classes of sub-disciplines have developed in fusion physics, each with related simulation codes

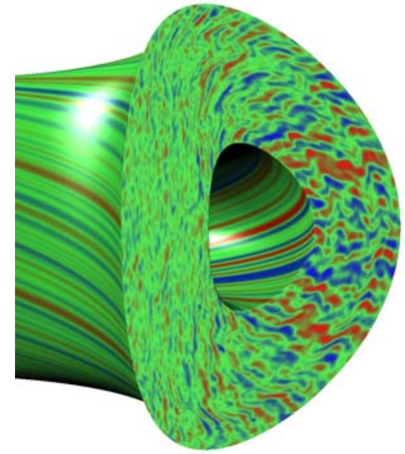
Hydromagnetic force balance of plasma pressure supported by J×B force

- MHD equilibrium
- Macroscopic fluid instability
- Current and magnetic field evolution



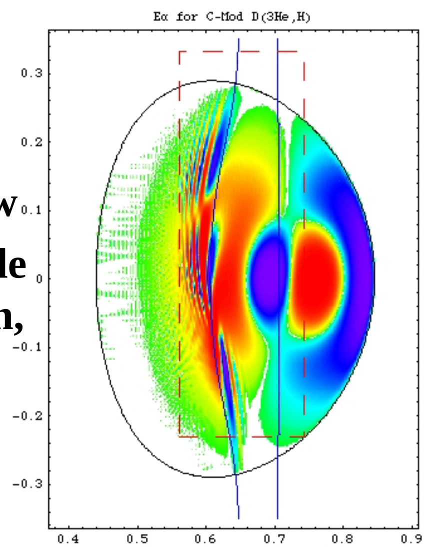
Kinetic stability and transport

- Micro-stability
- Turbulence and turbulent transport
- Long mean-free-path collisional transport
- Fusion heating



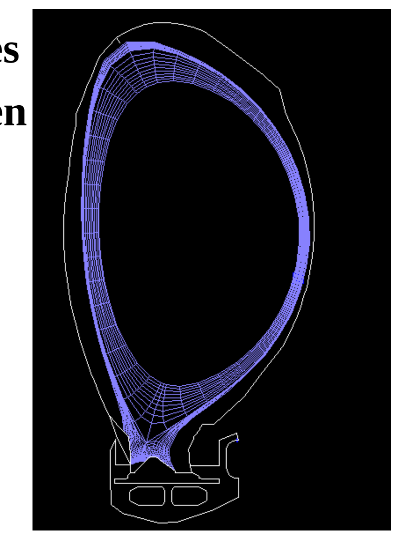
Injection of high-power waves or particle beams, magnetic flux

- Plasma heating
- Externally driven current or plasma flow
- Wave processes – mode conversion, absorption, reflection
- Non-Maxwellian particle distributions



Plasma/edge interactions

- Atomic physics processes
- Transition closed → open flux surfaces
- Transport on open field lines
- Turbulence
- Plasma/material interactions



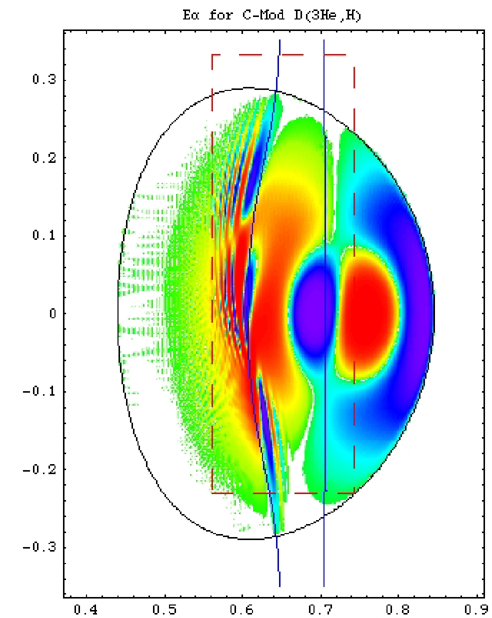
Objectives of CSWPI: understand heating to ignition, plasma control through localized heat, current and flow drive, $\tau < 10^{-7}$ sec

$$\nabla \times \nabla \times \mathbf{E} + \frac{\omega^2}{c^2}\mathbf{E} = \mathbf{J}_P \circ \mathbf{E} + \mathbf{J}_{ant} \quad : \quad + \text{boundary conditions}$$

$$\mathbf{J}_P(\mathbf{x},t) = e\int d^3v\,\mathbf{v} f_1(\mathbf{x},\mathbf{v},t) \qquad f_1(\mathbf{x},\mathbf{v},t) = -\frac{e}{m}\int_{-\infty}^{t} dt'\,\mathbf{E}_1(\mathbf{x}'(\mathbf{x},\mathbf{v},t'),t')\cdot\frac{\partial f_0}{\partial \mathbf{v}'}$$

plasma wave current: an integral operator on E

Plasma response is highly non-local → solve integral equation,large dense linear system



Quasi-linear – time average distribution function f_0 evolves slowly, described by time averaged Boltzman equation

$$\frac{\partial f_0}{\partial t} + \left(v_{\|}\hat{\mathbf{b}} + \mathbf{v}_{\mathbf{d}}\right)\cdot\nabla f_0 = C(f_0) + Q(f_0) + S$$

particle sources

flow along field lines

radial transport

collisional relaxation

quasi-linear RF

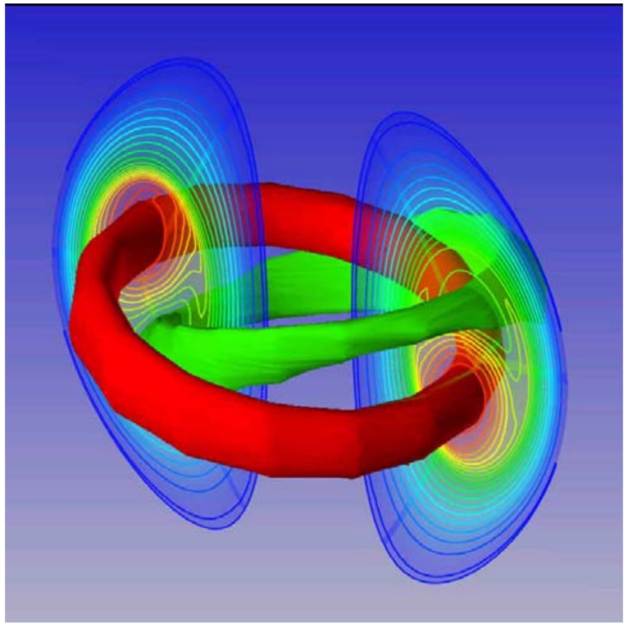
CEMM Objectives: Understand global force balance, and large scale, fluid-like instabilities that can limit fusion performance or even terminate the discharge

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{V}\cdot\nabla\right)\mathbf{V}=-\nabla p-\nabla\cdot\Pi+\mathbf{J}\times\mathbf{B}$$

$$\left(\frac{\partial}{\partial t}+\mathbf{V}_\alpha\cdot\nabla\right)p_\alpha=-\gamma\, p_\alpha\nabla\cdot\mathbf{V}_\alpha+(\gamma-1)(Q_\alpha-\nabla\cdot\mathbf{q}_\alpha)$$

$$\mathbf{E}=-\mathbf{V}\times\mathbf{B}+\eta\mathbf{J}+\frac{1}{en}\mathbf{J}\times\mathbf{B}$$
$$+\frac{1}{\varepsilon_0\omega_p^2}\left[\frac{\partial\mathbf{J}}{\partial t}+\nabla\cdot(\mathbf{JV}+\mathbf{VJ})+\sum_\alpha\frac{q_\alpha}{m_\alpha}(\nabla p_\alpha+\nabla\cdot\Pi_\alpha)\right]$$

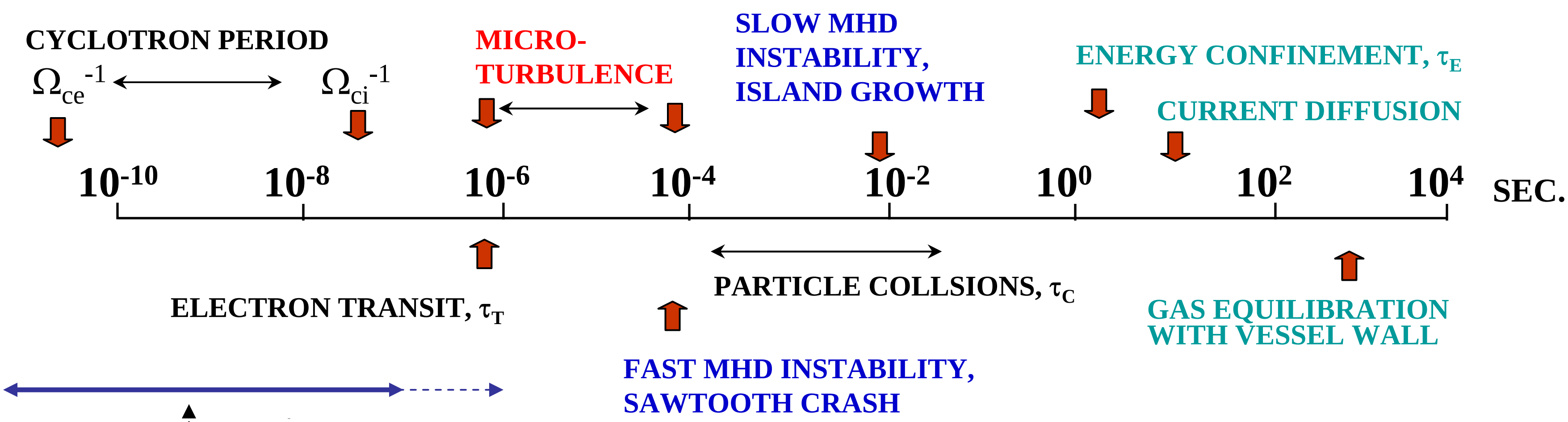
$$\frac{\partial\mathbf{B}}{\partial t}=-\nabla\times\mathbf{E}\,,\qquad \nabla\cdot\mathbf{B}=0$$



Snapshot of a 3D calculation of a reconnection event in a low-aspect ratio tokamak. Two iso-pressure surfaces are shown

- **(Extended) MHD codes describe gross plasma motion in a fluid model including extensions to kinetic and non-ideal effects, $\tau \sim 10^{-6} - 10^{-2}$ sec**

Even when the time scales are separated they can interact.
Long term goal – to include all relevant interacting processes



MHD and transport modifications to wave "medium"

RF Codes: wave-heating and current-drive Model: single frequency, static plasma background	Gyrokinetics Codes: micro-turbulence Model: kinetic, average over gyro-angle	Extended MHD Codes: device scale stability Model: fluid with kinetic extensions	Transport Codes: discharge time-scale Model: fluid, evolving equilibrium

RF induced plasma modifications:"quasilinear time-scale

SWIM is a pilot project for integrated fusion simulation, bringing together two, mature fusion disciplines. <u>Why these two?</u>

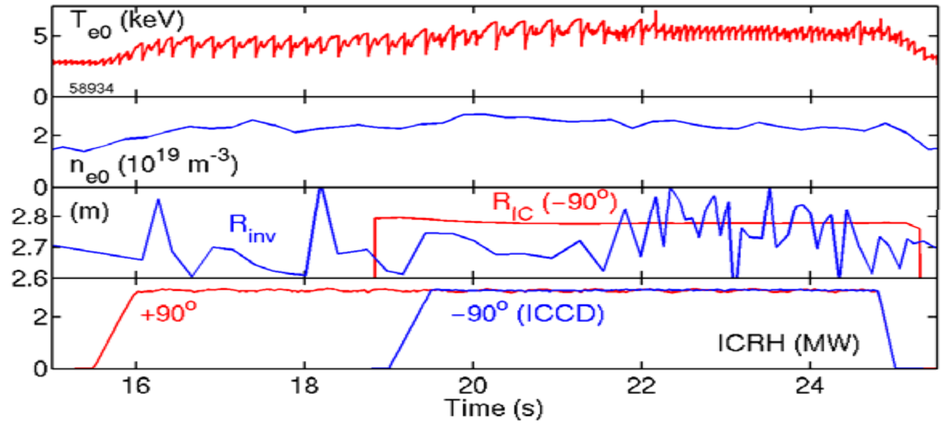
RF waves are demonstrated to influence MHD (either stabilizing or destabilizing). How will this scale to ITER or reactors?

ICRF stabilization on JET

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- **ICRF heating can produce "monster" sawteeth – period and amplitude increased**
- **Likely stabilization mechanism – energetic particle production by RF**

Sawtooth control on JET with Minority Current Drive on JET



- **ICRF minority current drive can either increase or decrease period and amplitude**
- **Likely stabilization/destabilization mechanism – RF modification of current profile**

Understanding and control of macro-instabilities is critical for the success of ITER